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Spectral Fluctuations in Centrifugal Impeller Outlet Flows

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ABSTRACT

Detailed measurements at outlet of a centrifugal impeller were carried out using hotwire anemometry. It was found that the flow is non-uniform across the blade pitch and showing a spectral unsteadyness with reference to time at the mean width of hub to shroud passage. Through an appropriate methodology of evaluation including Fourier Transformation (FFT) analysis, the flow properties were characterised for spacial and unsteady variations. Predominence of a frequency peak at three times the speed of revolution indicates the periodic formation and cross channel sweep of vortices within the impeller blade channel. This phenomenon would explain the deviations of real flow measurements from that obtained by assuming a uniform relative eddy or a jet-wake flow in the impeller channel.

INTRODUCTION

The flow inside a centrifugal impeller is complex both in spacial domain as well as in time domain. It is largely three dimensional with variations in blade to blade and hub to shroud planes. And in a rotor, unsteady variations could be induced due to finite number of blades used. The design and analysis of impeller flows are based on assumption of quasi-three dimensionality with distributed body force to simulate the presence of blades[9]. In centrifugal impellers coriolis force due to relative vorticity of rotation is very significant. The channel geometry is highly diffusive and leads to large cross channel variations and shear flows. Steady state equillibrium of forces cannot be sustained in such flows and a predominance of secondary flows arising out of vortex layers are being noticed inside the impeller[2,3]. Formation of vorticity fronts in shear flows have been discussed by various authors[4,11]. Coherent fluctuations with a defined frequency are detected on the suction surface of elliptic cylinders at an angle of attack[7]. These are distinguished from Kàrman vortex street shed from the trailing edge of aerofoils. These fluctuations are characterised by the Strouhal Number. Vortices formed either due to a boundary layer or the evolution of a shear flow can lead to the phenomenon of rotating stall in cascaded passages. Propagating stall in linear cascades have been studied through vortex simulation [10]. Potential flow theory along with empirical modelling such as the concept of slip due to relative eddy and jet-wake hypothesis are generally used to compute the impeller outlet flow conditions[4,5,8]. All these assume the flow to be steady both in relative frame and in absolute frame of reference. Unsteadyness is considered only in terms of large scale turbulence of random nature particularly in the boundary layer or wake region. Measurements using hot-wire anemometry and a proper analysis of the same in the present investigation indicate a periodic phenomenon of unsteadyness with coherent spectral variations. This paper describes such characterisation, of flow velocity and angle at impeller outlet both in the spacial and time domain, through an appropriate evaluation procedure.

EXPERIMENTAL MEASUREMENTS

A centrifugal impeller of 525 mm diameter and 45.5 mm width at outlet, having 23 blades backswept by 40° with reference to radial direction was used for experimental measurements of outlet flow. This impeller was rotated at 5000 rpm by a thyristor driven DC motor maintaining the speed to an accuracy of 0.1%, through feed back control. It was provided with a well designed bell mouth intake and a throttle valve at downstream, after a vaneless diffuser and a large volute chamber. The facility was instrumented for global measurements of mass flow, pressure, speed and power. Detailed investigations of flow at outlet were carried out using a linearised constant temperature hot-wire anemometry system. For unsteady flow investigations, this system is advantageous as compared to other sophisticated systems like laser anemometry which depend on statistical averaging technique.

A hot-wire probe placed 8 mm radially outwards of the impeller as shown in Figure 1 was used in two directions to measure radial and whirl components of velocity in a dynamic mode at impeller outlet, mid-way between hub and shroud faces. From these two trace measurements, the absolute velocity and absolute angle of flow at outlet, were calculated. A signal conditioner and a lineariser were part of the anemometry system.

The hot-wires were calibrated separately in a steady uniform flow, wherein flow velocity and angle could be accurately monitored to about 1 m/s. and 1^o respectively. For experimental measurements, the linearised signals were fed to a computer-controlled dual beam signal analyser (FFT analyser) and the data were recorded through its memory on to magnetic discs in digitised form. The instrumentation system lay out is shown in Figure 1b. An once per revolution spike was generated from a magnetic pick up, mounted near a projection in the shaft. This was used to trigger the hot-wire traces and data were recorded for a duration of 50 milli-seconds, corresponding to nearly four revolutions of rotor. Over this period, the signal was digitised into 4096 data recordings, which provided a frequency response of 20 kHz. Compared to this, rotational frequency of the rotor was 83.2 Hz and blade passing frequency was 1.9 kHz only. 50 Such recordings, one after another, in a phase-locked manner couldbe obtained to get the ensemble average of a signal, consisting of a duration to cover 92 blade passages. The recorded data correspond to equal intervals of time. From this data, the flow property variations with respect to angular traverse of impeller and the variations at a given angular position on the impeller with respect to time were derived using computer algorithms. The Forward Fourier Transformation analysis of the later data, derived from measurements was carried out off-line using a separate computer programme.

RESULTS

The measurements of signals from the radial and tangential hot-wires are shown in Figure 2. These show radial velocity and whirl velocity variation at a flow coefficient of 0.5. A continuous signal, over four revolutions of impeller covering 4 x 23 = 92 blade passages, was captured for each wire. For clarity the variations of velocity over the time taken to traverse two pitch distances of blade passage are given in Figure 2b. The variation of flow with respect to traverse time within one blade pitch across the blade-to-blade channel is quite apparent. In the suction side half of the blade channel, the radial velocity is markedly low coupled with a higher tangential velocity. In the rest of the passage the velocities are closer to the design value estimated from taking into account a conventional slip factor and blade outlet angle. This distinct characteristic is modelled in the classical jet-wake flow hypothesis [1,12,13]. In this model, the flow is considered to be separated into two regions; a jet region near the pressure side wherein potential flow as per design exists and a wake region near the suction side having a reduced relative velocity, with a shear layer separating the two regions. The relative flow angles in the two regions, however, are assumed to be the same as the value estimated from slip and blade outlet angle to substantiate the presence of shear layer. This would give rise to a variation of slip in the respective regions. The reduced relative velocity in the wake region leads to a larger absolute velocity. Assumption of relative flow angle to be the same would give rise to reduced slip; hence a slip factor of unity with zero slip is generally taken for this wake region. At closer look of the measurements, the absolute flow angle in the wake region could be seen to be much larger than that derived from taking blade angle as relative flow angle. Analysis of flow structure in terms of velocity and angle, particularly in the relative frame would provide more clarity. Using the measurements of radial and whirl components of flow and the impeller peripheral speed, the velocity and angle both absolute and relative could be computed. These are shown in Figures 3a, 4a, 5a & 6a. As modelled in the jet-wake hypothesis, the relative velocity shows a distinct jump across the passage with a reduced value near the suction surface and increasing to a higher value near pressure surface. However, the relative flow angle, instead of being nearly the same as the blade angle, throughout the passage, a large variation is seen in the wake region near the suction surface. In these figures the variations are shown against traverse time. Conversion of these variations to one with respect to spacial distance traversed, as described below, would show that this jump in relative velocity occurs well within the passage and cannot be linked with formation of a separated boundary layer wake. These characteristics which are not considered in the jet-wake hypothesis are studied in detail here.

Hot-wire signals obtained as variations with respect to time at the point of probe location in the stationary frame can be traced back as flow variations with respect to space within the passage as the impeller sweeps across the probe. The flow properties measured at a given time uniquely correspond to flow emanating from a specific point on the impeller, depending on the relative location of the probe and the relative triggering of the signal with respect to a particular blade. Generally, when the flow is steady, time-wise capture of velocity can be considered equivalent to variations with respect to relative angular position given by ωt. Since the probe is located at a finite distance of 8 mm radially outwards from impeller tip and the absolute flow direction is not radial, the actual point, from where the flow left the impeller to reach the probe will have an angular

...from probe radial line and also the measured ...city will correspond to the velocity on impeller point at a time, earlier than the recorded instant time by an amount Δt. In an unsteady flow the relative angular position whose velocity was captured would change due to the above two factors by an amount $\Delta\theta - \omega \cdot \Delta t$. These shifts in angular position and time could be computed by assuming momentum conservation in the absolute flow field outside the impeller. The actual velocity with which flow left the impeller will also be calculated by correcting for the small amount of variation in radial locations of impeller point and probe. As detailed in Reference 8, these factors could be accurately taken into account and the flow properties in the relative frame of impeller outlet obtained as spacial variation across the passage from suction surface to pressure surface. Such a transformation carried out for individual blade passages are shown in Figures 3 to 6. While figures appended with 'a' give the flow property as captured by the probe in the stationary frame, figures appended with 'b' give the same transformed to the impeller outlet of blade passage. Figures 3a, 4a, 5a and 6a are with respect to time, while Figures 3b, 4b, 5b and 6b are with respect to spacial location, in terms of normalised angular co-ordinate at impeller rim. Variations in two widely different passages are super-imposed one on the other in these figures to show the qualitative similarity and quantitative variation since these two passages were captured at different instances of time. The location of the two blades encompassing the passage with their suction and pressure surfaces are marked in the figures. The corresponding relative velocity and relative flow angle are also computed and are shown in Figures 5b and 6b. As measurements were taken over four revolutions of the impeller, the flow across all the 92 blade channels shown in Figure 2 could be transformed in the above manner. The blade channels are identical with uniform inlet flow conditions and all of them exhibit this type of fluctuating characteristic over the same portion of the channels at various times. With this similarity as basis, the unsteady characteristic of the flow at a given location of the impeller channel, in the rotating frame could be obtained by plotting the fluctuating component of velocity or angle, at corresponding points in each channel with respect to the exact time, at which the flow emanated from the impeller rim. Such characteristics for different locations in a blade channel (6 in number) are plotted in Figures3c, 4c, 5c and 6c. These locations are marked as numbers 1 to 6 in Figures 3b, 4b, 5b and 6b.

DISCUSSIONS

A study of Figures 3 to 6 reveal an interesting observation. The flow variations in Figures 3a, 4a, 5a and 6a are monotonic with time. However, when transformed, the variations, as computed, are not monotonic with spacial distance in Figures 3b, 4b, 5b and 6b. This means that the probe senses the flow from the same point in one blade channel more than once, within the sweep time of traverse for this one channel. In fact, flow sensing or measurements over a certain distance are seen to have a back and forth oscillatory nature in some passages. A clear inference of this is that the flow at these points within the relative frame is fluctuating with respect to time. Both magnitude and direction of velocity fluctuate with time and the variations are smooth, so that the sensing point in the relative frame moves back and forth over this distance of the channel. A simpler imaginary situation would help in explaining this. If for instance one imagines that the flow at a given point on the impeller rim has a flow direction which is changing with time at the same rate but opposite in direction, at which the imepller angular rotation sweeps across the probe, then the very same point will be sensed over a period of time, though the channel traverses across the probe. Extending further if this flow direction change is more than the impeller rotational speed, one can see that the sensing point will move forward further and already traversed points will be sensed again.

By a transformation of the hot-wire signals, picked up as time-wise variation at a point in the stationary frame, to a space-wise variation of flow in the rotating frame along with the exact time of its occurrence in the rotating impeller and a closer study of the same, it is seen that the flow is unsteady and fluctuating within the rotating frame itself. What is more interesting is that these fluctuating flow properties, in different channels of the impeller, shown in Figures 3c,4c, 5c and 6c are coherent and can be analysed for their regular periodicity. The fluctuations are significant only at a few stations and not uniformly seen at all stations within the channel. These figures show respectively the fluctuating component of velocity and angle both absolute and relative at various stations inside a blade channel. Six stations have been identified with one each near the suction and pressure surfaces and four stations within the channel where oscillations are large. The angular location of the station from the suction surface of the forward blade, covering the passage, and the average value of velocity or angle are given along-side each plot at the right. The abscissa is time, normalised to the duration of measurement viz. four revolutions. The ordinate is marked with velocity or angle intervals to indicate the magnitude of fluctuations respectively. Markings to indicate the time duration for each revolution as well as each blade passage are also shown. It is apparent that there is a large fluctuation of velocity and flow direction at the fourth station internal point, which is beyond the mid point towards pressure side between suction and pressure surfaces of the channel. The fluctuations, at stations within the passage, show a coherent structure in that they are periodic but the periodicity does not coincide with either impeller rotation or individual blade passage.

The absolute velocity near the suction surface is slightly higher than the desiggn value and has an attenuated amplitude of oscillations. As one moves towards the pressure surface across the channel, the magnitude of velocity increases to about 154 metres per second at station 2 and the oscillations are seen to be increasing in amplitude. Just beyond this point, at stations 3, 4 and 5, the oscillatory amplitudes are large though the average velocity has come down. Very near to pressure surface at station 6, the average velocity is close to design value with negligible oscillations. Similar characteristics are seen in absolute angle variation also. Near the suction surface the outlet flow angle is compatible with relative flow being at blade outlet angle with reduced velocity and the oscillations are very small. At stations 2 and 3, the oscillations are seen to have grown while the average value is higher. Stations 4 and 5 show a much more clear periodicity of flow oscillations but the average angle has come down. At the pressure surface, the flow angle variation with time is negligible and the average magnitude is close to the design value. The relative velocity and relative flow angle variations, with respect to time at these six stations in the channel are shown in Figures 5c and 6c. The variations are similar to those obtained with absolute flow properties though these are highly marked in the case of relative flow angle than in the case of relative velocity. The relative flow velocity near the suction surface is 35 m/s and reduces to 32 m/s at station 2 and 33 m/s at station 3, well inside the passage. Looking at 5b, it is seen that the relative velocity in fact decreases from a high value of 50 m/sec on suction surface to 35 m/sec at station 1. This shows that the reduced relative velocity in this region could not have been due to a separated wake from the suction surface. The fluctuations are minimal at this station, but show a clear periodicity with coherence. At stations 4 and 5 the fluctuations are much larger and the average relative velocity is also increased to 41 m/s and 52 m/s respectively. Very near the pressure surface relative velocity is 67 m/s with negligible but periodic oscillations. The relative flow angle variations are characterised in a distinguished manner. The average value near the suction surface station 1 is close to the blade outlet angle of 40^ with very little oscillations, showing that the flow is not separated. Inside the channel moving towards the pressure surface, the relative flow angle is reduced very much and becomes even negative, but having increasingly large fluctuations. The amplitude of fluctions are largest with $\pm 20^0$ at station 3 where the average relative flow angle is -9^0. Further towards the pressure surface, the average relative angle increases to 31^0 at station 4 and is further increased to 45^0 at station 5 with reduced fluctuations. Near the pressure surface the fluctuations are negligible and the relative flow angle is 53^0 showing a slip angle of 13^0 over the blade outlet angle of 40^0. The oscillations in relative flow are significant in the following way while the angular fluctuations are much larger at stations 3 and 4, the velocity fluctuations are dominant slightly beyond at stations 4 and 5. It could be visualised that a vortex core was exiting out between stations 3 and 4 and had its origin inside the channel between stations 2 and 3. The vortex core has a sense of direction opposite to impeller rotation and a cross channel sweep towards pressure surface in the relative frame. The origin could have been in the channel shear flow itself near the suction surface and not necessarily the boundary layer on it. The measurements have been taken at outlet and hence the influence of vortex core, when formed inside the channel on velocity and angle fluctuations at station 2 are not large. However, when leaving the impeller between stations 3 and 4, the vortex core being nearer to the point of measurement, the fluctuations are much larger at stations 4 and 5.

In order to evaluate the periodicity of the fluctuations, the flow velocity and flow angle were analysed through Forward Fourier Transformation. The FFT analysis of velocity and angle at the above six stations within the blade channel are given in Figures 7 to 10. Both frequency spectrum and auto correlation were obtained and plotted. In the frequency spectrum of all cases analysed, there is invariably a maximum peak at 83.2 HZ, which corresponds to 5000 RPM of impeller rotation. The data have been collected over four revolutions and a periodicity of once per revolution as above, establishes that the flow is channel pitch-wise symmetrical, over the angular direction, at any given instant and there is no rotating stall type of phenomenon observed at this flow coefficient. The 20.8 HZ peak corresponds to the period over which data have been collected and is of no relevance.

The frequency spectrum of all the parameters at stations 4 and 5 show a peak at or near about 250 HZ which corresponds to 3 cycles within one revolution of impeller. This is also corroborated by the autocorrelation of the signal. At periodic intervals corresponding to 250 Hz, there is a dip or disturbance seen in the autocorrelation data. In fact, at the station 5, autocorrelation of absolute flow angle shows a clear periodicity of 12 cycles over four revolutions of data

...orresponding to 3 cycles for each revolution ...eller, and the maximum peak of frequency ...ctrum occurs at 250 Hz, rather than that corresponding to impeller rotational RPM. The frequency spectrum peak near 250 Hz is predominant at stations 3 to 5, wherein the fluctuations are large in the time domain also. This is true of all the flow properties both absolute and relative. At station 2 however, the mean flow properties are largely affected to deviate from the design. The mean relative flow angle is seen to be the lowest at -29° (about 69° away from the guiding blade angle) and the absolute velocity is maximum at 154 m/s compared to the design value of 100 m/s obtained at the blade surfaces. Though amplitude of fluctuations at this station 2 are small, they are also characterised by a frequency peak near 250 Hz. It is to be remembered that the measurement and analysis of flow is at impeller outlet, whereas, the origin of any disturbance would be well within the passage and should be travelling out with the flow. Any unsteady disturbance would affect the mean flow to a maximum extent at the point of its presence and its influence will be reduced at other points as the disturbance diffuses into the flow field as discussed earlier.

The foregoing analysis of FFT of velocity and flow angle signals indicate that the flow inside the impeller has a periodic disturbance at 250 HZ corresponding to 3 times for every revolution of the impeller. The disturbance has the characteristic of a vorticity with a sense opposite to the direction of rotation, originating in the channel moving across the flow and exiting out of the impeller farther away from the suction surface of the blade channel. Hence, the flow in the suction side half of the impeller passage is influenced by these vorticity disturbances to deviate from the design. The flow very near the pressure surface of the blade does not seem to be influenced by these disturbances except that it is deflected to show a slip.

CONCLUDING REMARKS

Similar to characterisation of vortex shedding, in flow past cylinders, by Strouhal Number, this case of impeller flow also shows a resemblance. The disturbing vortices in the flow should have their origin near the suction surface of the blades well inside the channel and they are found to have travelled in this case half the blade channel across the flow before exiting and coming out clear of the impeller. In view of this, half the channel pitch at impeller outlet can be taken as the linear dimensional parameter for computing Strouhal number. Since the flow of vortices out of the impeller is governed by the radial through flow velocity of the flow, this radial component of velocity is taken as the other parameter. With these parameters, the Strouhal number for this particular case works out to be 0.25, which compares very well with the universal value of 0.2. This point only reinforces the above inference that the unsteady flow observed at impeller outlet is characterised as having a coherent structure due to periodic formation of vortex type of disturbances near the blade suction surfaces and travelling out across the passage. It is to be emphasized again that this vortex formation has not lead to a total separation of flow on the blade suction surface unlike the consequence of a boundary layer growth. This phenomenon is responsible for the reduced relative velocity as well as angle and increased work on the flow in the suction side half of the passage and also for the increasing relative velocity and angle of flow near the pressure side, leading to what is known as slip. The periodic formation and cross channel movement of such vortices could also be the cause of initiation of rotating stall in impellers.

ACKNOWLEDGEMENTS

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NOMENCLATURE

C	Absolute Velocity
P	Pressure surface
S	Suction surface
t	Time
Tc	Traverse time for one blade Channel
Td	Time for Data collection over four revolutions
U	Blade tip peripheral velocity
W	Relative velocity
α	Absolute flow angle from radial direction
β	Relative flow angle from radial direction
θ	Angular distance from suction surface
θ_C	Angular distance of one blade Channel
$\Delta\theta$	Angular shift of traversed point from probe
Δt	Time for travel from traverse point to probe
ω	Angular speed of rotation

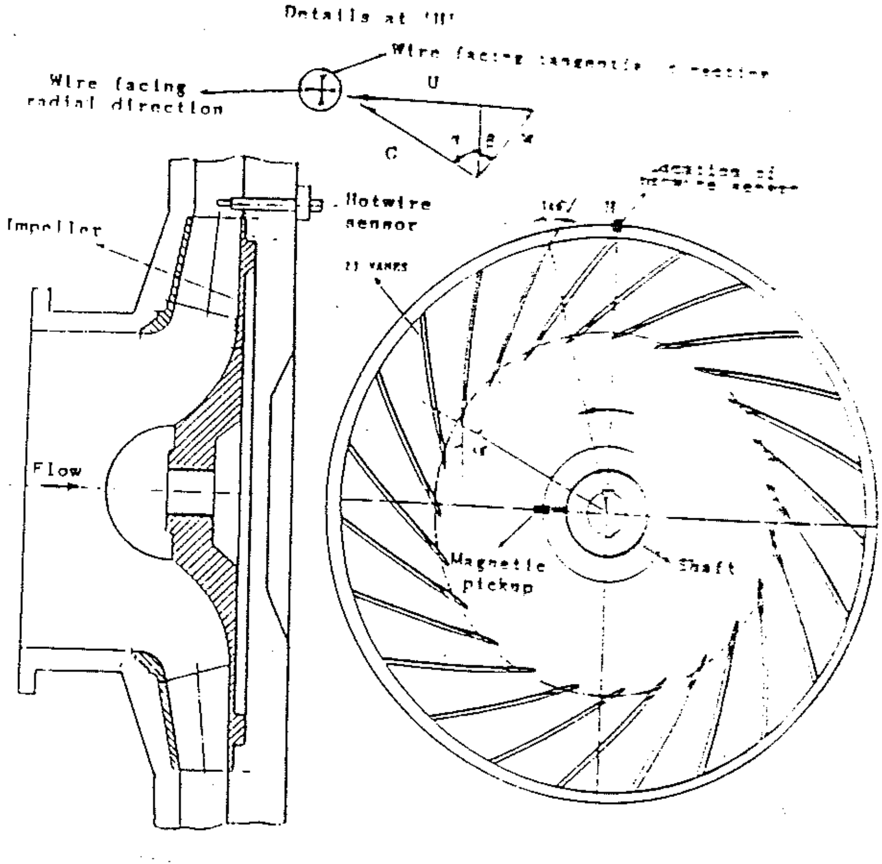

Figure 1a. Test Impeller

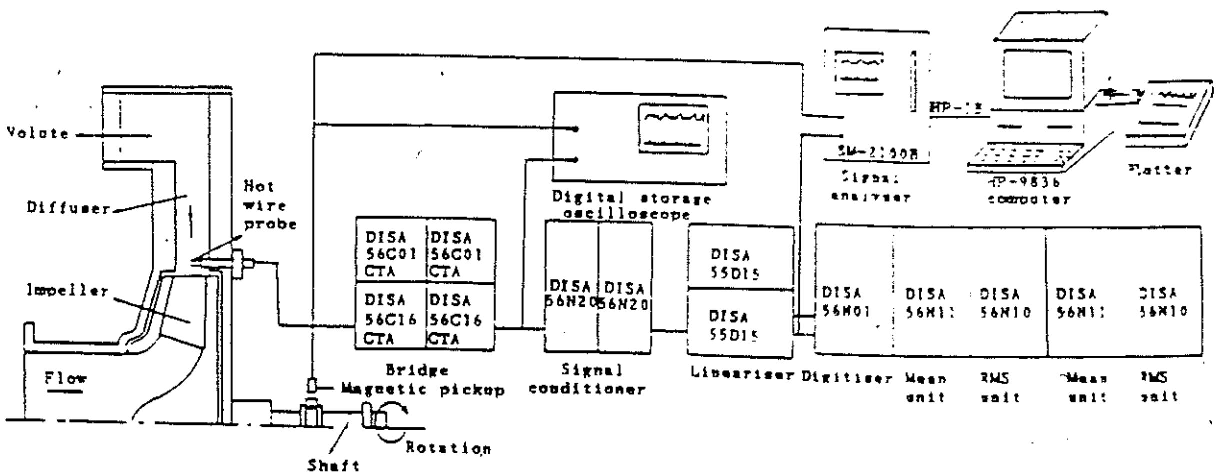

Figure 1b. Hot wire instrumentation

Figure 1. Experimental set-up

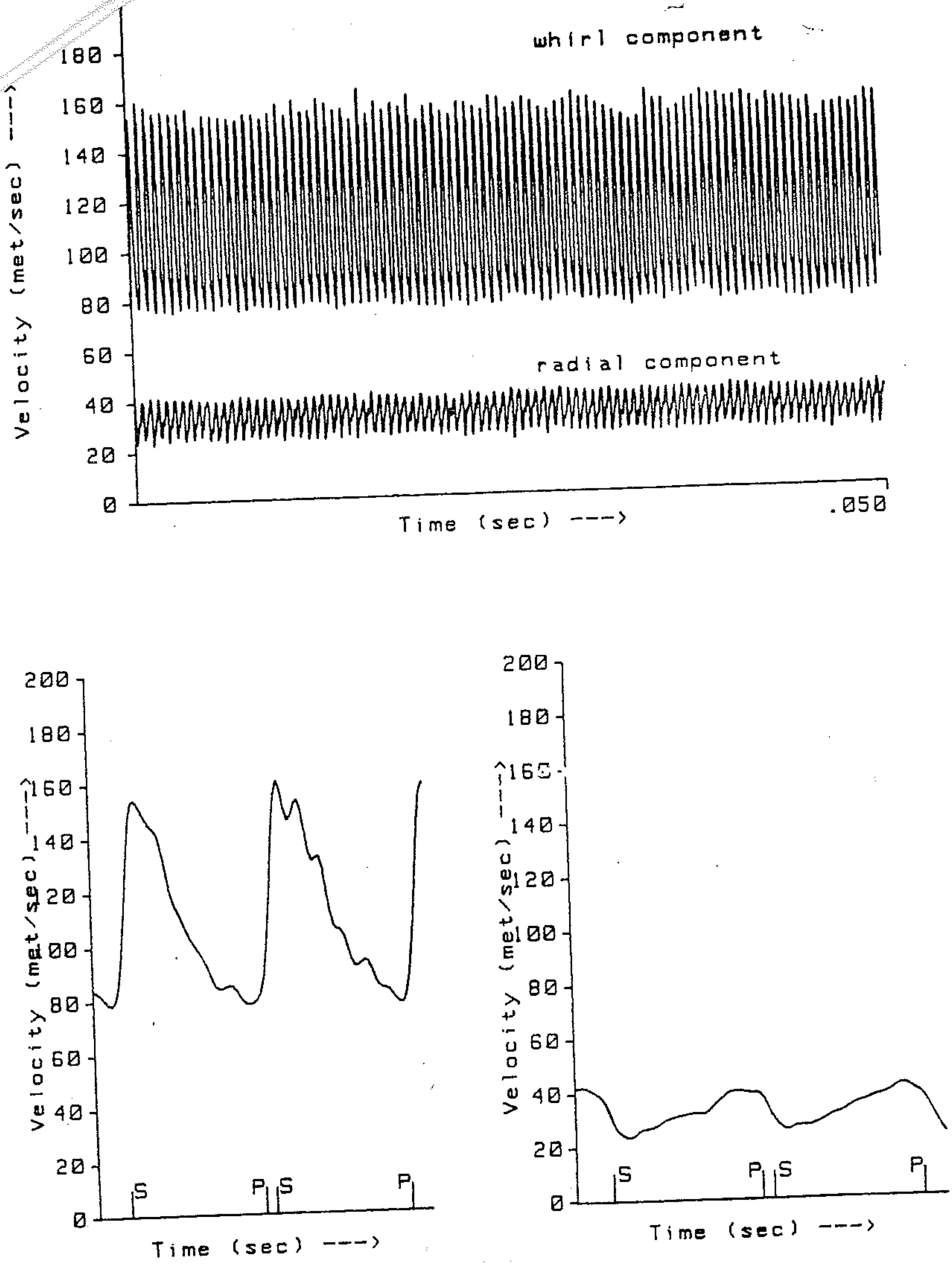

Figure 2. Hot wire measurements

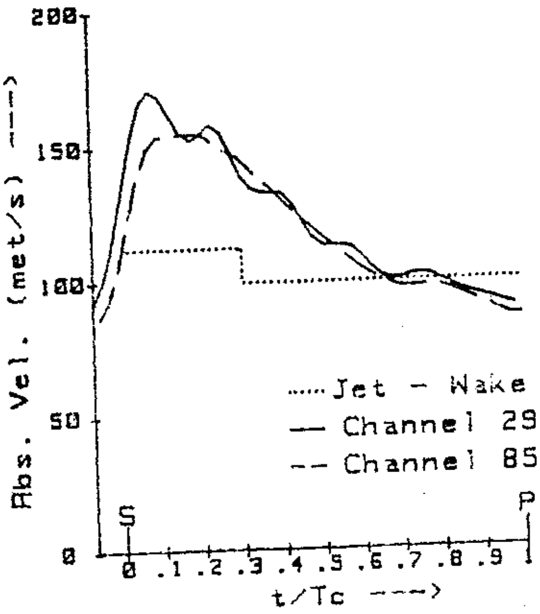

Figure 3a Temporal variation

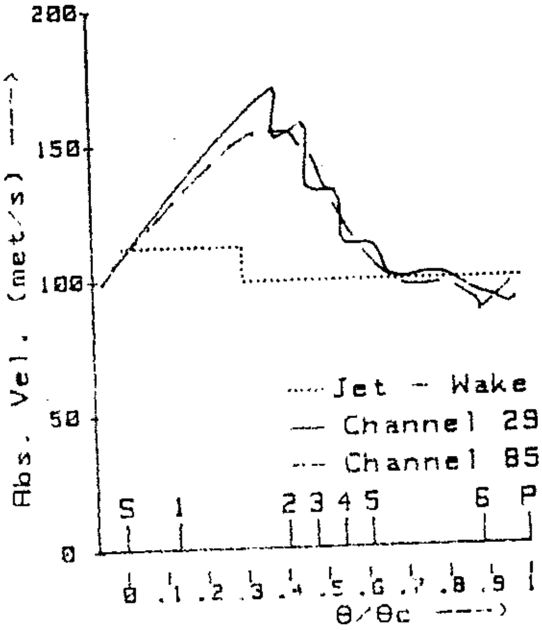

Figure 3b Spatial variation

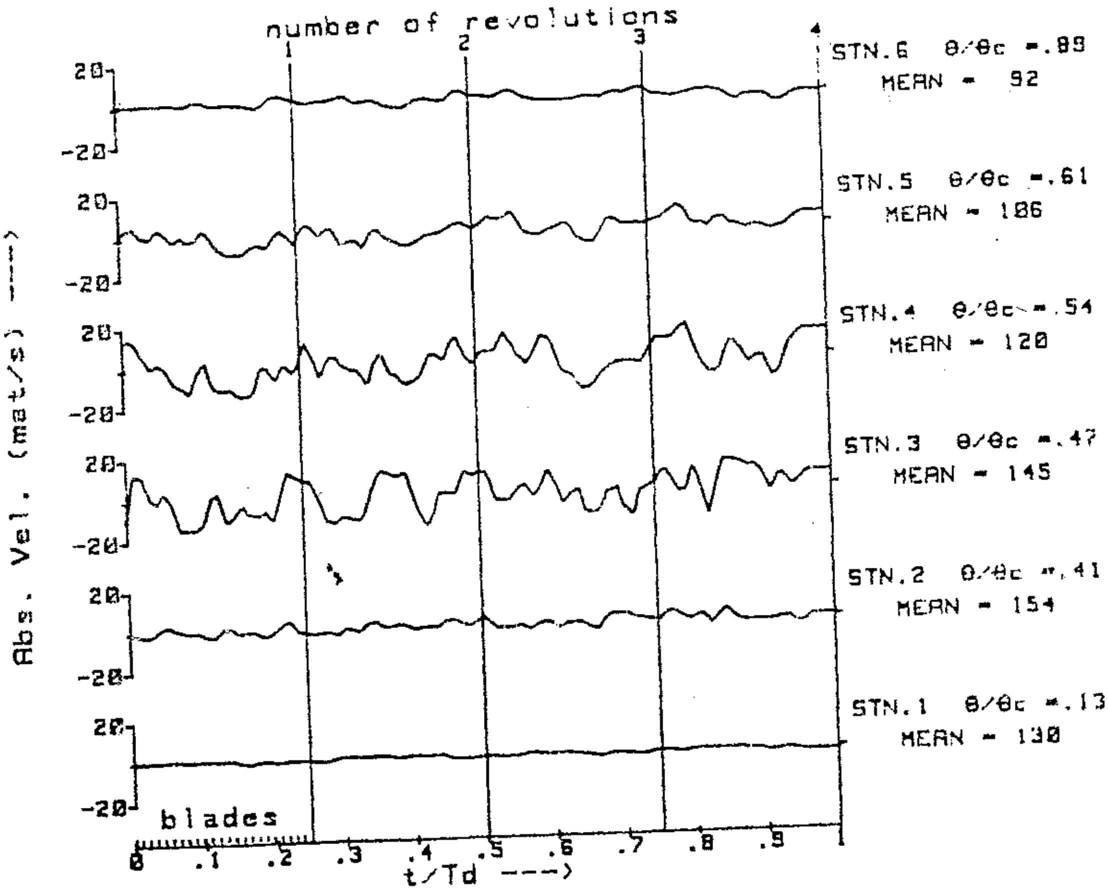

Figure 3. Characterisation of Absolute velocity

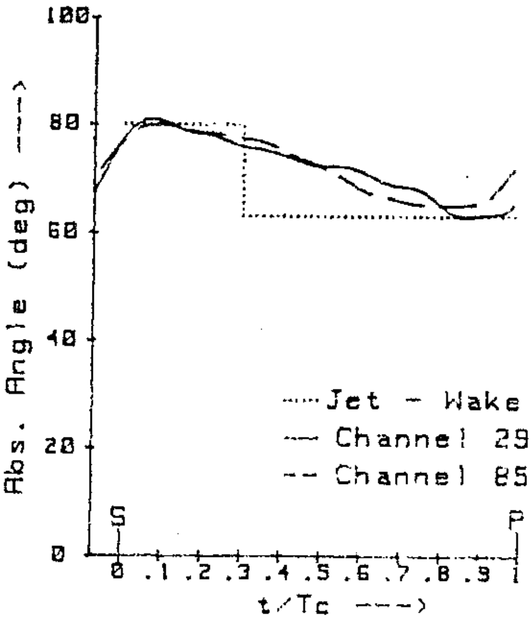

Figure 4a Temporal variation

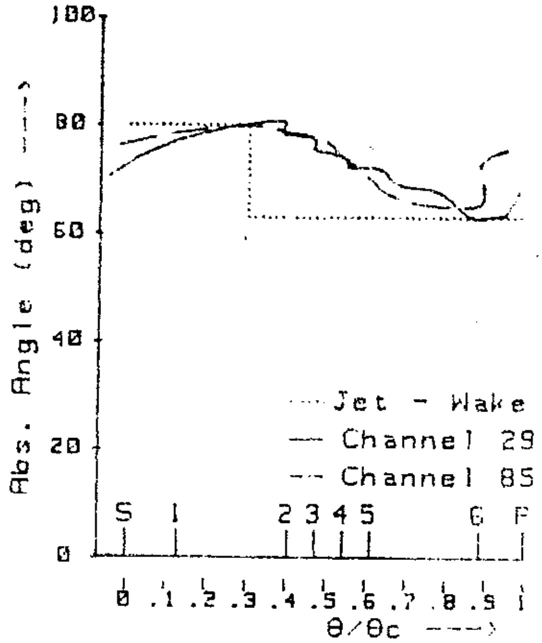

Figure 4b Spatial variation

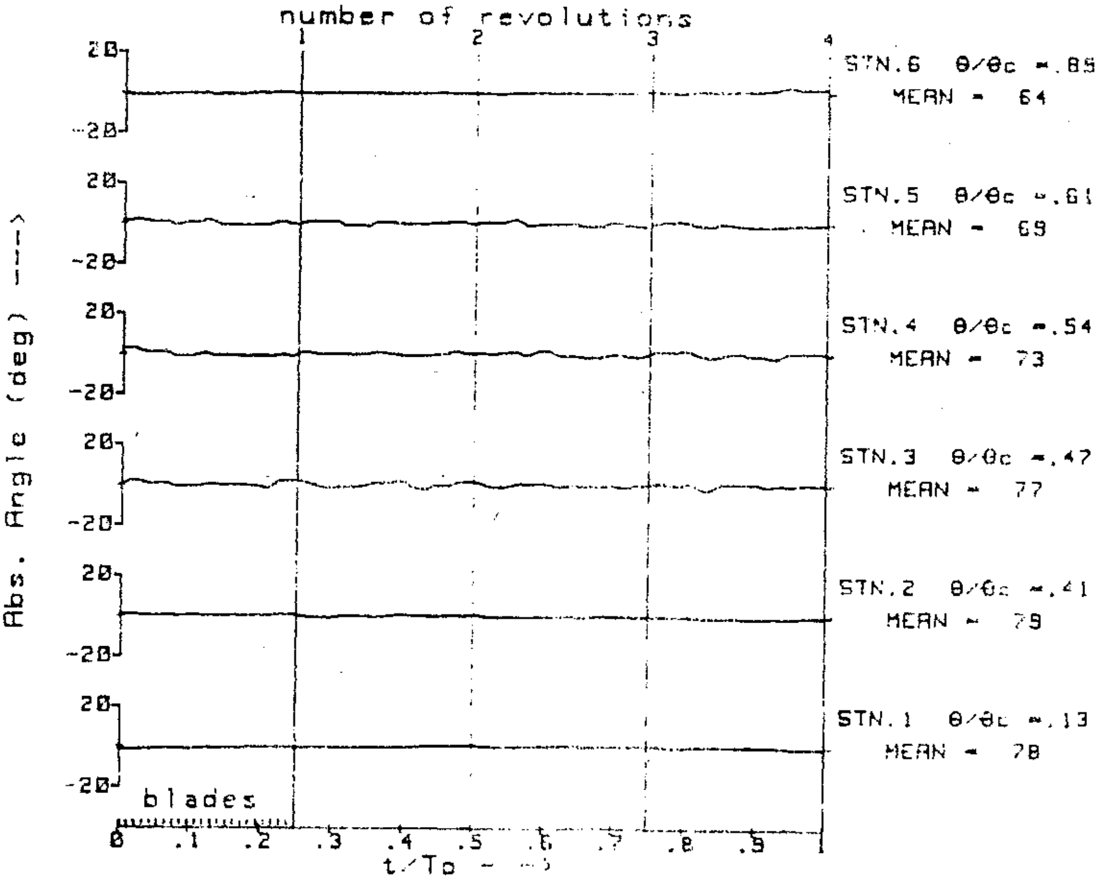

Figure 4 Characteristics of Absolute Angle

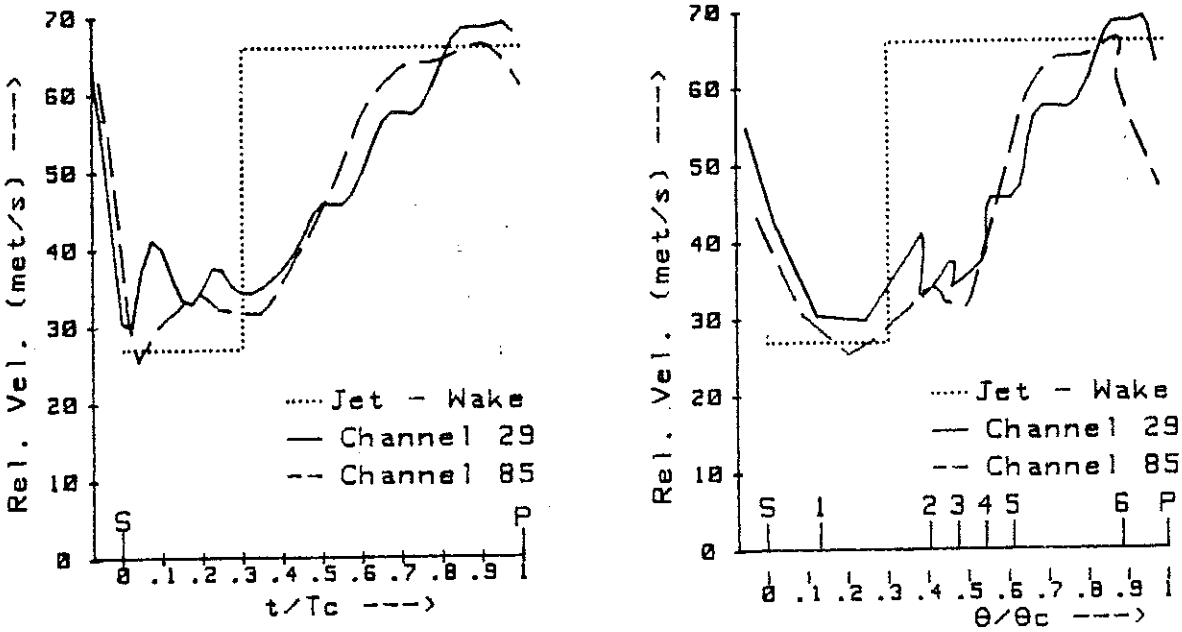

Figure 5a Temporal variation

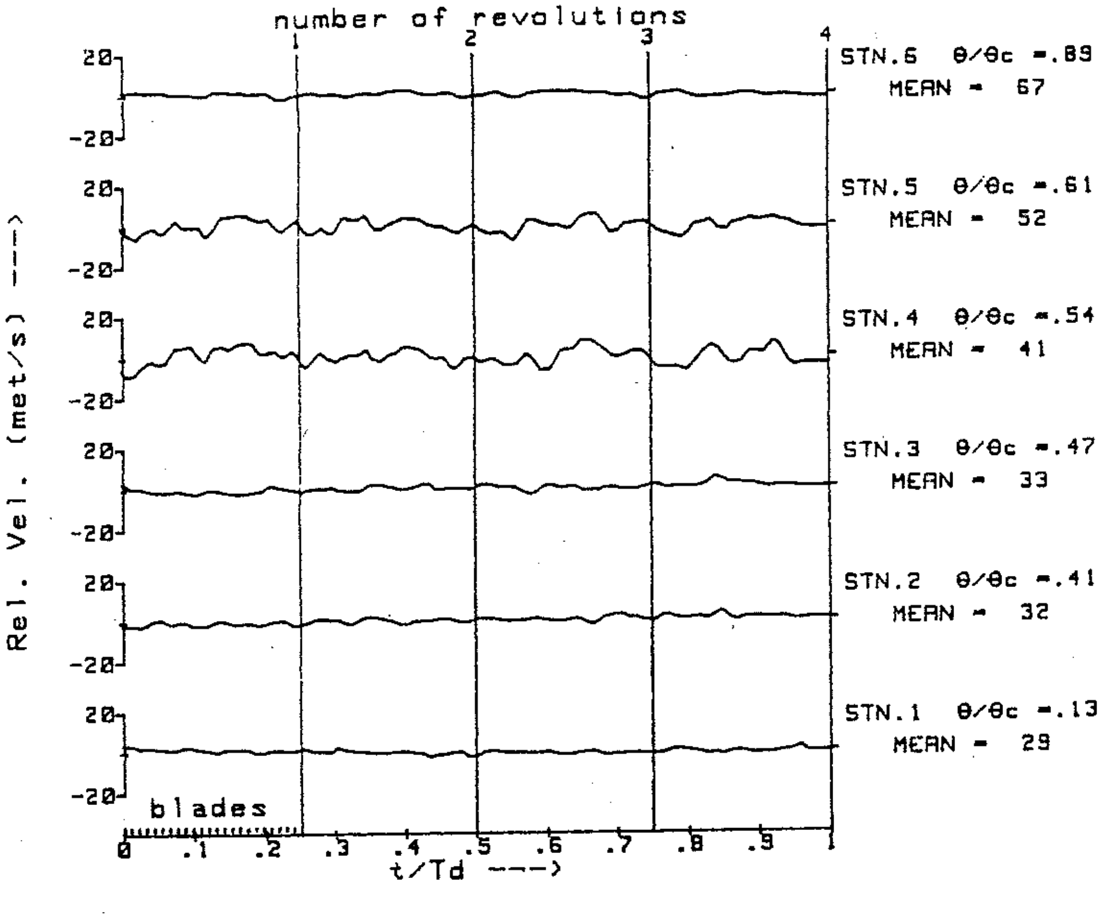

Figure 5 Characteristics of relative velocity

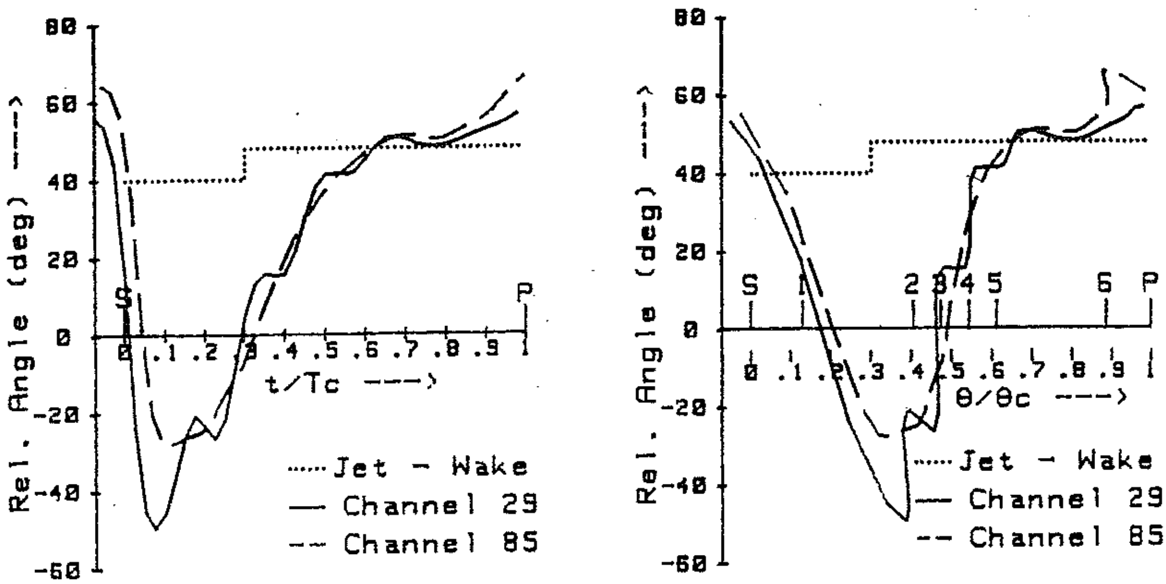

Figure 6a. Temporal variation

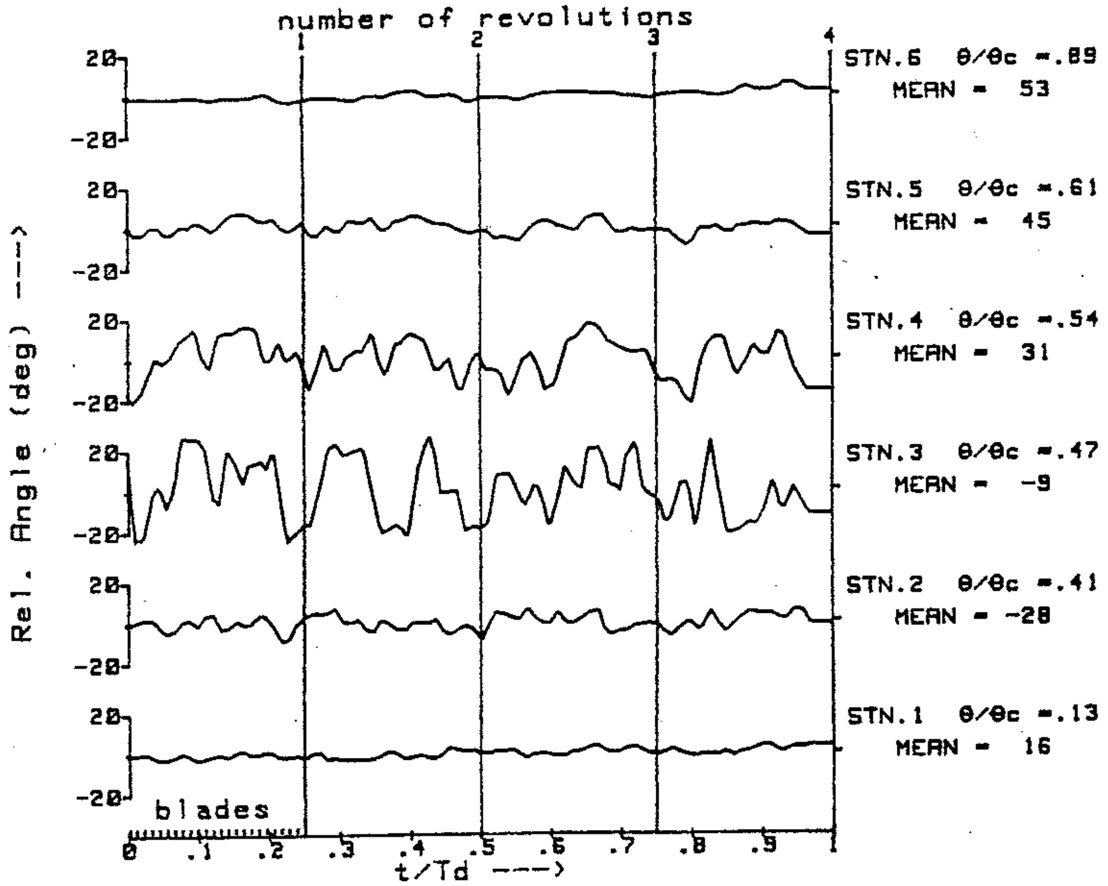

Figure 6b. Spatial variation

Figure 6. Characteristics of relative angle

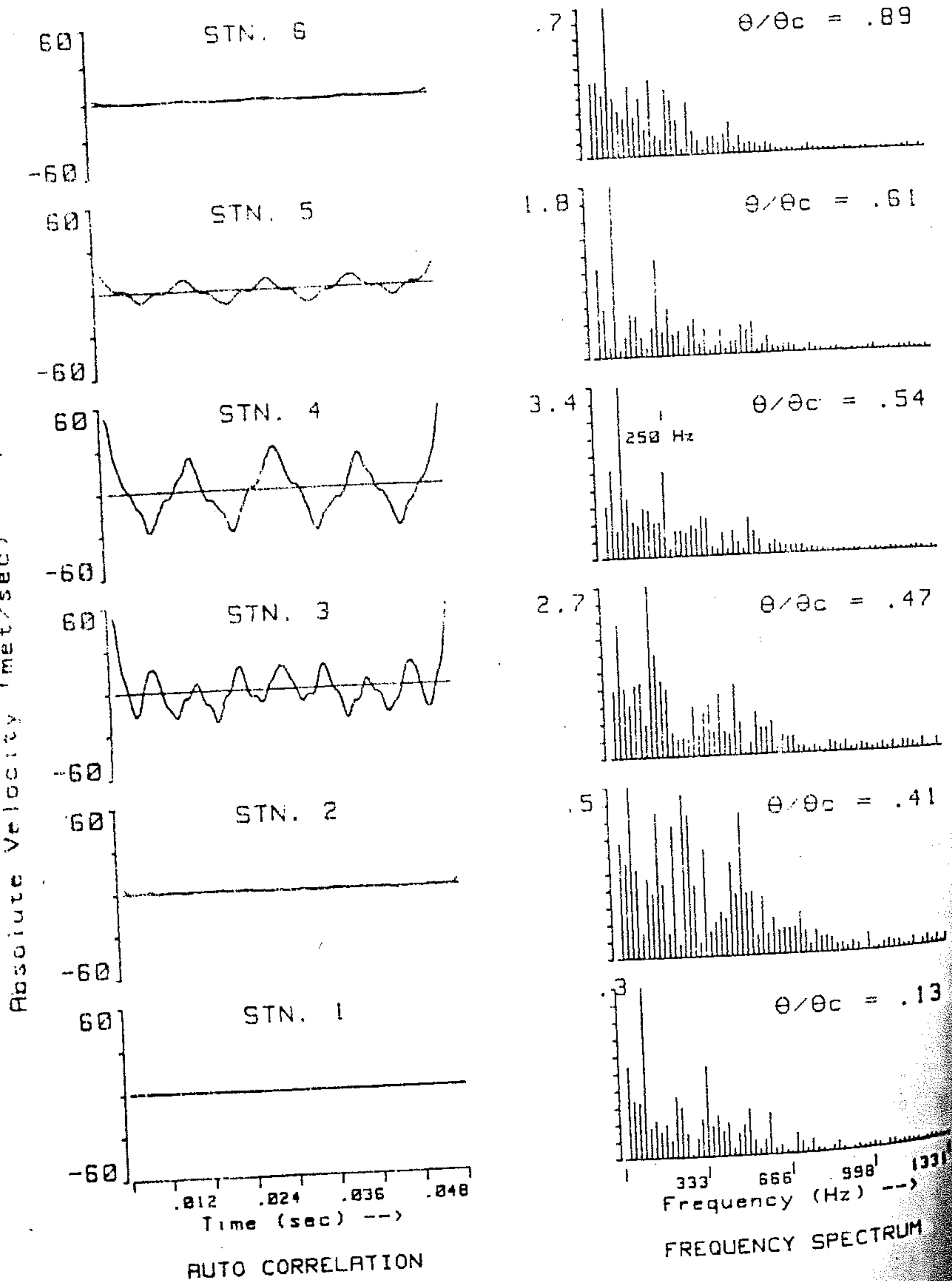

Figure 7. Fourier transformation - Absolute velocity

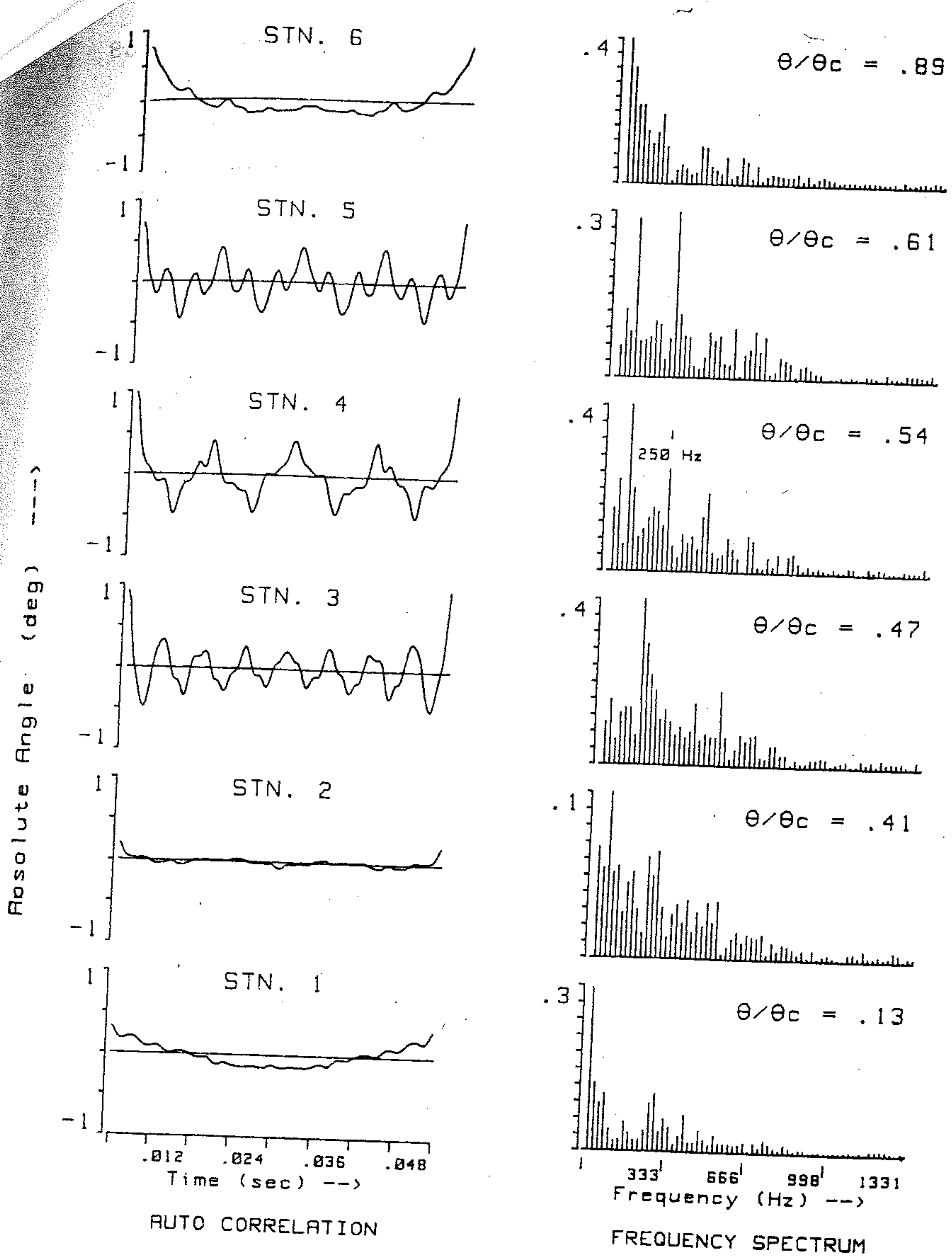

Figure 8. Fourier transformation - Absolute angle

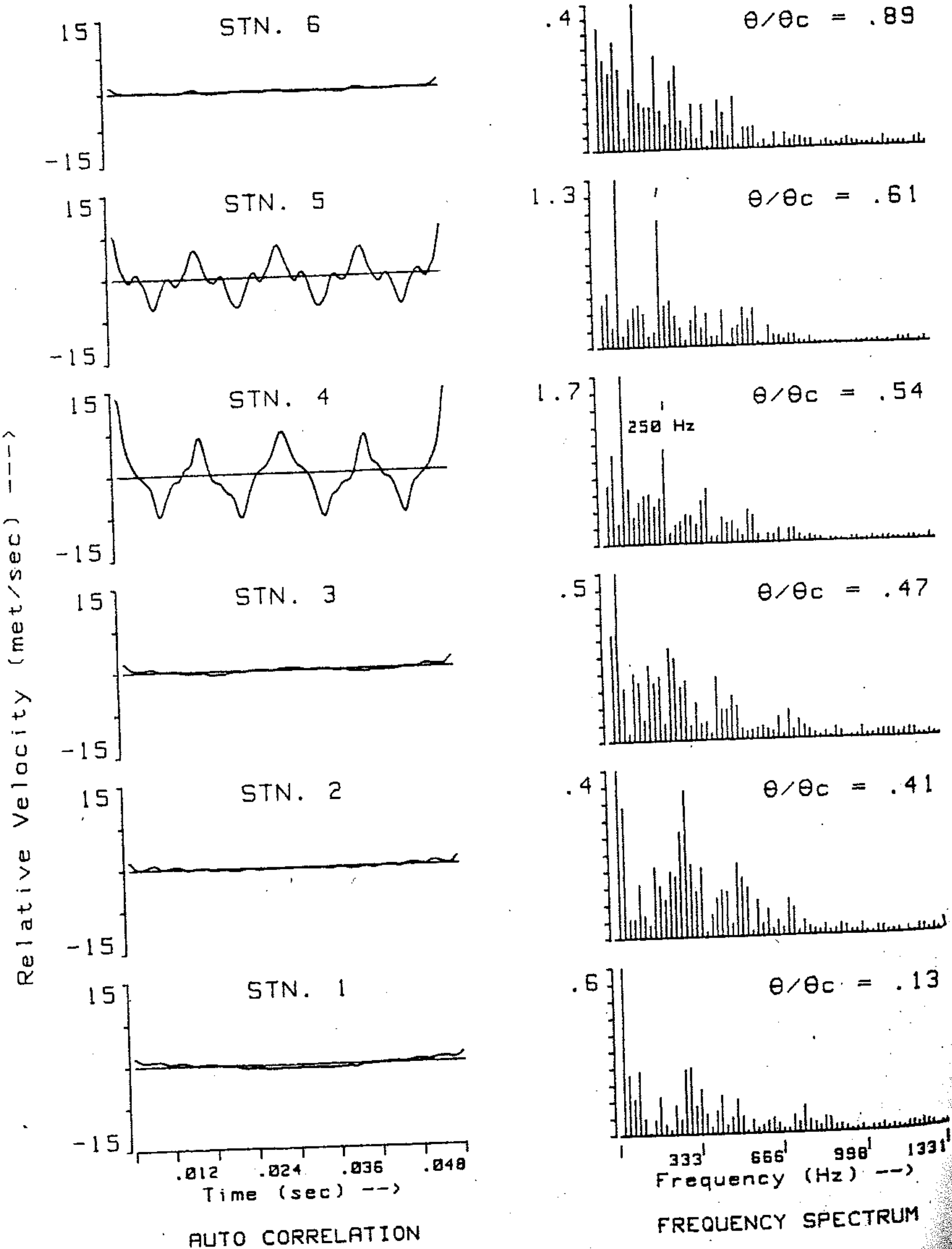

Figure 9. Fourier transformation - Relative velocity

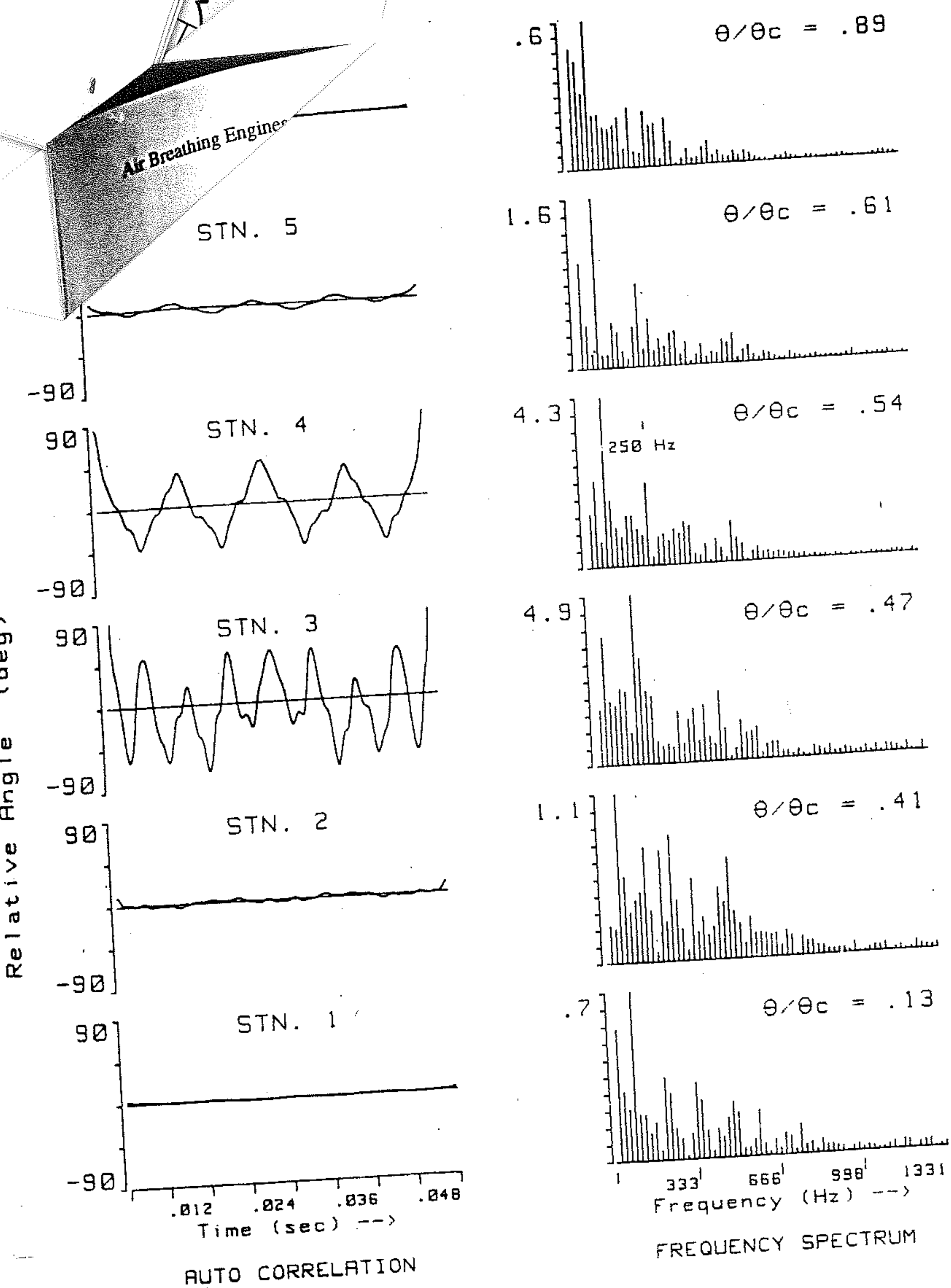

Figure 10. Fourier transformation - Relative angle.